2001-08

THE ASTROPHYSICAL JOURNAL, 549:320–324, 2001 March 1

COSMIC-RAY SOURCES AND SOURCE COMPOSITION

C. H. TSAO AND R. SILBERBERG
Physics Department, 221 College Lane, Roanoke College, Salem, VA 24153
AND
A. F. BARGHOUTY
Space Radiation Laboratory, California Institute of Technology, MC 220-47, 1200 East California Boulevard, Pasadena, CA 91125
Received 2000 June 9; accepted 2000 October 31

ABSTRACT

Present data on cosmic-ray elemental and isotopic relative abundances are shown to be unable to distinguish between various models of cosmic-ray sources and their composition. For example, the model of freshly nucleosynthesized material from supernova explosions as the cosmic-ray source is unable to account for some measured, key cosmic-ray elemental abundances. This and two other models are evaluated here in light of recent isotopic and elemental measurements. It is shown that model-dependent preferential injection, acceleration, and reacceleration do not allow a clear distinction of one model against the others. Future measurements of critical elements and isotopes are suggested, which should afford us the ability to do that. We base our suggestions on measurements and a quantitative comparison between the predictions of the standard leaky-box model for the Galactic propagation of cosmic rays and one in which reacceleration is taken into account.

Subject headings: acceleration of particles — cosmic rays — Galaxy: abundances — nuclear reactions, nucleosynthesis, abundances

1. INTRODUCTION

While the first-generation Population III stars essentially consists of H and He only, the first- and/or early generation cosmic rays are relatively rich in products of nucleosynthesis, as inferred from their spallation products Li, Be, and B, condensed into early low-metallicity stars (Lingenfelter, Ramalty, & Kozlovsky 1998).

First-generation stars are massive ($\sim 100\ M_\odot$; Bromm, Coppi, & Larson 1999; Irion 1999). As these stars reach the red or blue supergiant phase, they lose much of their outer envelope, after which the presupernova stellar wind, known to be rich in the helium-burning products carbon and oxygen, is emitted (Silberberg et al. 1990). Maeder & Meynet (1994) and Massey et al. (1995) find that the production of Wolf-Rayet (W-R) stars is strongly dependent on metallicity and is much less for low-metallicity stars. However, this reduction comes about because of a mass threshold for stars that become W-R stars. The threshold is 25 $M_\odot$ for a metallicity $Z = 0.02$ and 80 $M_\odot$ for $Z = 0.001$. For the first-generation (Population III) stars of masses near 100 $M_\odot$, production of W-R stars need not be suppressed.

Supernova shock waves accelerate the stellar wind particles (rich in newly nucleosynthesized nuclei) to cosmic-ray energies. For the present-day Galactic cosmic rays, the acceleration of the presupernova stellar wind particles, especially from Wolf-Rayet progenitors, contributes to C, O, and ^{22}Ne. Afterward, supernova shock waves accelerate particles from the interstellar gas. The present cosmic-ray data do not permit a clear differentiation between first ionization potential (FIP) dependent injection from stars into interstellar space (Cassé, Goret, & Cesarsky 1975; Meyer 1985) on the one hand and significant contribution to acceleration and breakup of grains of the trans-H and trans-He cosmic-ray nuclei (Meyer, Drury, & Ellison 1997) on the other. Future abundance measurements of Ge should provide the crucial test.

A comparison of the inferred Galactic cosmic-ray (CR) source abundances with the general elemental abundances (GAs, which, to a high degree, are based on solar and meteoritic abundances) shows large similarities but also some significant differences. The latter permit the construction of various models of cosmic-ray origin as well as judgement of merits and difficulties of these models. It is the purpose of this paper to evaluate these models and to propose crucial future tests that, in principle, can help delineate the basic, model-independent astrophysical scenarios consistent with Galactic cosmic-ray measurements at 1 AU.

This paper is organized as follows: Section 2 surveys the differences between the cosmic-ray source composition and the general abundances. Section 3 discusses the model that analyzes those differences in terms of a preferential FIP injection and explores the differences in the low- and high-FIP transition regions of solar flares and coronal nuclei versus Galactic cosmic rays. Section 4 compares the model in which volatility and grain formation and breakup are the crucial parameters with the FIP-based model. Section 5 explores the model in which the newly nucleosynthesized nuclei of supernovae are accelerated to dominate the heavy component of cosmic-ray nuclei.

Section 6 explores the relative abundances of the actinides (Th, U, and to a lesser degree Pu) and how the radioactive decay of their isotopes permits the estimation of the mean age and age distribution of these nuclei in cosmic rays and presumably of other nuclei formed by nucleosynthesis in supernovae. Section 7 compares the results of Galactic propagation calculations, performed with and without reacceleration, with available cosmic-ray data. In § 8 we list some uncertainties and discuss suggested future tests against the backdrop of the models we evaluated.

2. GENERAL ELEMENTAL ABUNDANCES AND SOURCE COMPOSITION OF COSMIC RAYS

The general elemental abundances, including that of the

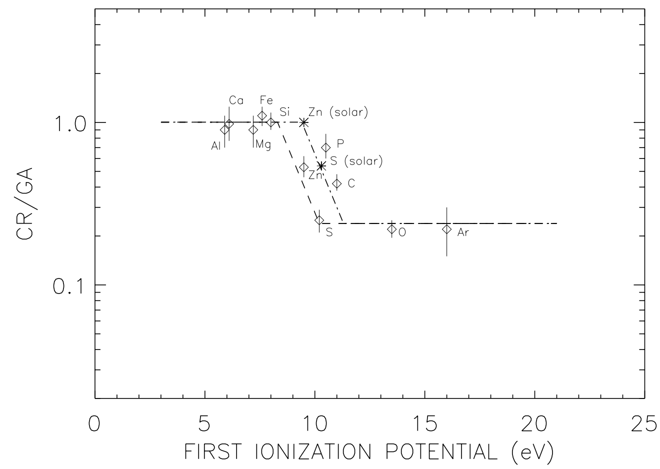

FIG. 1.—Low-to-high FIP transition energy and comparison of cosmic-ray and solar coronal or flare particle data.

Sun, are made up of the primordial H and He, including heavier nuclei formed by H and He burning, C and O burning, Fe-abundance peak formation by the addition of a series of He nuclei to Si, and the slow and rapid (*s* and *r*) neutron-capture processes that proceed up to Pb and the actinides ($Z \geq 90$).

The elemental and isotopic abundances of cosmic rays, when corrected for spallation in the interstellar gas back to the source(s), tend to resemble the general abundances (Anders & Grevesse 1989; Grevesse & Sauval 1998) but also display some significant differences. The general abundances are based on solar spectra and carbonaceous chondrite meteorites. The abundances between H ($Z = 1$) and Pb ($Z = 82$) decrease by some 10 orders of magnitude. Relative to GA, the elements H and He are underabundant in CRs by a factor of 20–30 and N by about 10. The nuclide ^{20}Ne is underabundant by a factor of 6, the elements O, S, Ar, and Kr by a factor of 4, and C, P, Zn, Se, Xe, and the nuclide ^{22}Ne by a factor of 2. However, the *r*-process part of the lanthanides and Pt is overabundant in CRs by a factor of 2, and the *r*-process actinides (Th and U) are overabundant (before radioactive decay) by a factor of about 4.

3. ORIGIN IN PRESUPERNOVA STELLAR WIND AND FIP-MODIFIED STELLAR PARTICLES

The expanding supernova shock waves encounter first the region of the presupernova stellar wind. Silberberg et al. (1990) proposed that the initial phase of acceleration by supernova shock waves boosts many of the presupernova stellar wind particles to cosmic-ray energies. These stellar wind particles, especially in the W-R stars, are enriched (Meyer 1981) in products of He burning, ^{12}C and ^{16}O, and of N burning in the helium zone that yields ^{22}Ne via $^{18}\text{F} \to {}^{18}\text{O}$ and $^{4}\text{He} + {}^{18}\text{O} \to {}^{22}\text{Ne}$.

As the shock waves reach beyond the presupernova stellar wind region, they accelerate the particles injected by stars in interstellar space. The composition of these particles is considered in this model by photosphere-to-corona particle escape that is dependent of the first ionization potential (Havnes 1971; Cassé et al. 1975; Meyer 1985). High-FIP elements are suppressed relative to the low-FIP ones. If the first ionization potential is less than 10 eV (which corresponds to a temperature of $\sim 10^4$ K), these elements tend to have higher abundances. This has been discussed and illustrated by Silberberg & Tsao (1990). A recent version of injection by low-mass flare stars is that of Shapiro (1997).

The data of Binns et al. (1989) suggest an enhancement of the *r*-process elements at and beyond the *r*-process peak at Xe ($Z = 54$). Similar to Ar, Xe (a high-FIP element) should have a value of ~ 0.25. An enhancement factor of 2 yields the observed value of 0.5. The lanthanides are also enhanced. Spallation of Pt contributes to the lanthanides, and these spallation products may dominate in the so-called heavy secondary (HS) region ($70 \leq Z \leq 73$). However, the contribution of spallation products to the light secondary (LS) region ($62 \leq Z \leq 69$) should be less, since the cross sections with large mass difference of the LS elements are smaller (see eq. [1] of Shapiro & Silberberg 1970). Yet, the abundance of the LS elements per unit charge exceeds that of the HS elements by a factor of 2 (Binns et al. 1989). Thus, the primaries dominate among the LS elements, and from Figure 6 of Binns et al. (1989), one can conclude an enhancement factor of 2 for these predominantly *r*-process elements.

The transition energy (above which nuclei are suppressed by a factor of ~ 4) differs for the Sun and cosmic rays, as shown in Figure 1; the transition energy is lower for cosmic rays. The element Zn is in the middle of the transition region for cosmic rays, while it is in the low-FIP, unsuppressed region for the Sun, as inferred from solar flare particles (Anders & Grevesse 1989). The element S is in the high-FIP, suppressed region for cosmic rays, while it is in the middle of the transition region for the Sun (Anders & Grevesse 1989; Feldman et al. 1998).

Table 1 shows the relative abundances of elements S and Zn (normalized with respect to Si), which are at the FIP transition region. The data are from Meyer et al. (1997) for cosmic rays and from Grevesse & Anders (1989) for solar particles. The values for cosmic rays versus solar particles differ by 2 standard deviations for both S and Zn. Further measurements and subsequent interpretation are desirable. If one adopts the FIP-based model, the difference in the cosmic-ray and solar transition energies (note that the transition energy is correlated with stellar temperature and mass) implies that cosmic-ray injection sources are less massive than the Sun.

TABLE 1

CR SOURCE/GA AND SOLAR PARTICLE/GA RATIOS

Abundance/In	Sulfur	Zinc
Cosmic rays	0.30 ± 0.04	0.5 ± 0.1
Solar particles......	0.52 ± 0.10	1.4 ± 0.5

4. PREFERENTIAL ACCELERATION OF NONVOLATILE OR REFRACTORY ELEMENTS

In this model the grains are accelerated by shock waves of supernova remnants, break up, and then are accelerated to cosmic-ray energies more readily than the volatile elements (Bibring & Cesarsky 1981; Sakurai 1990; Ellison, Drury, & Meyer 1997; Meyer, Drury, & Ellison 1997). Just like in the model discussed in § 3, according to this model, the initially accelerated particles are those of the presupernova stellar wind, rich in helium-burning and N + He–burning products C, O, and ^{22}Ne.

In general, volatile elements have high values of FIP, and both models make similar predictions with regard to the cosmic-ray source elemental abundances. However, there are a few exceptions, which should help delineate the merits of one model versus the other. We shall now explore these elements, listing them in order of their atomic number.

Na is a low-FIP but semivolatile element. Its CR/GA ratio is lower by about 40% than that of the low-FIP elements. However, it also fits the low-Z suppression factor of Silberberg & Tsao (1990), which slightly suppresses elements with $Z \leq 12$, less so for Mg than Na but more so for ^{20}Ne and still more so for the lighter elements.

The element P has a high FIP but is also semivolatile. The measured value is consistent with the prediction of the grain volatility model but deviates from the prediction of the FIP-based model by nearly 2 standard deviations.

The elements Cu and Ga are low-FIP but semivolatile. They both fit the FIP-based model. Cu is at or even above the FIP line of Meyer et al. (1997) by 1.2 ± 0.2 and Ga by 1.6 ± 0.6. However, with the mass-dependent factor of Meyer et al. (1997), they are also consistent with the grain volatility model.

Ge is a low-FIP and volatile element. With its GA based on the meteoritic abundances, its CR/GA ratio is 0.6 ± 0.1, i.e., it appears to fit the grain volatility model. However, the new measurement of 0.8 ± 0.2 by George et al. (1999) appears to be larger but only by 1 standard deviation. If further data from the Cosmic Ray Isotope Spectrometer experiment on board the *Advanced Composition Explorer* spacecraft support the measurement of George et al. (1999) and reduce the standard deviation, the case for the grain volatility model will be made weaker. On the other hand, if the GA value is based on solar abundances (Anders & Grevesse 1989; Grevesse & Sauval 1998), consistent also with the solar particle measurements of Sollitt et al. (1999; which, however, suffer from large uncertainties), the cosmic-ray data tend to favor the FIP-based model. Thus, the present data on Ge do not yield conclusive evidence for the grain volatility versus the FIP-based model.

The CR/GA abundance ratio of the high-FIP, highly volatile Kr is similar to Ar, i.e., consistent with the FIP-based model. In the grain volatility model (Meyer et al. 1997) with mass dependence, the CR/GA abundance ratio should exceed that of Ar. The data thus favor the FIP-based model but only to within 1 standard deviation.

Either model fits the data for Xe, assuming that the r-process elements at and beyond the Xe peak are enhanced by a factor of 2, which is consistent with the lanthanides, especially the LS group of Binns et al. (1989) for Pt and the actinides (see discussion in § 3).

The CR/GA ratio of the meteoritic abundance of Pb agrees with the grain volatility model according to Westphal et al. (1998). They reported the Pb abundance relative to the Pt group that is smaller by ~ 3 than the FIP prediction. However (as in the previous paragraph), assuming that r-process elements at and beyond the Xe peak (i.e., Pt) are enhanced by a factor of 2 or more (Binns et al. 1989), the results are consistent with the FIP-based model as well. However, with r-process enhancement of the Pt group by 2 or slightly more, the Pb/Pt ratio results in a fit consistent with the experimental ratio.

Thus, only P and Kr provide conclusive evidence for the two models, P for the grain volatility model and Kr for the FIP-based model.

There are two arguments that tend to support the FIP-based model: (1) The cosmic-ray high-FIP elements are suppressed by the same factor (~ 4) as the solar coronal or solar flare high-FIP elements. (2) The model of Meyer et al. (1997; see their Fig. 6) has too many (eight) fitting parameters, so as to fit the different CR/GA ratios for refractories, semivolatile, volatile, and highly volatile elements, each with its own characteristic coefficient for the mass- or charge-dependent acceleration process. The FIP-based model has fewer parameters when using (*a*) the coronal FIP curve, (*b*) light-ion suppression for $Z < 12$, and (*c*) heavy r-process enhancement by a factor of ~ 2.

5. MODEL OF ACCELERATION OF NEWLY NUCLEOSYNTHESIZED NUCLEI FROM SUPERNOVAE

Simplified forms of this model were proposed 30 years ago by Hayakawa (1969) and Shapiro & Silberberg (1970) and more recently by Yanagita, Nomoto, & Hayakawa (1990), who made detailed elemental abundance predictions. The model of Lingenfelter et al. (1998) was proposed on the basis of the linear increase of Be relative to heavier nuclei in stars formed at various stages of Galactic nucleosynthesis. (Note that Be is formed by direct spallation of, or induced by, cosmic rays.) If cosmic rays are derived from the interstellar medium (either directly or via flare particles), the early generation cosmic rays would have such a preponderance of H and He that not enough Be (or B) would be formed. In addition, this argument is made stronger by the fact that the early interstellar medium also has so few C, N, and O nuclei. Hence, cosmic rays must have been formed out of a concentrated, i.e., relatively undiluted, and relatively freshly nucleosynthesized source. Most Li, Be, and B is derived from C and O. Such a concentrated source of C and O (i.e., of newly nucleosynthesized helium-burning products) is naturally provided by the presupernova wind of the massive first-generation Population III stars (Bromm et al. 1999; Silberberg et al. 1990; see the second paragraph of their introduction).

An argument against prompt acceleration of heavy nuclei from the interior of the supernovae was presented by Wiedenbeck et al. (1999), based on the constraint of the time delay between nucleosynthesis and acceleration of greater than 10^5 yr. Using the latter constraint, Higdon, Lingenfelter, & Ramaty (1998) proposed a model based on the acceleration of material in bubbles with multiple supernova remnants. In this model, after nucleosynthesis, the acceleration takes place predominantly after 10^5 yr and up to the bubbles' lifetime of 5×10^7 yr, so as to allow ^{57}Ni to decay before acceleration (the half-life of ^{57}Ni is $\sim 10^5$ yr).

6. THE ACTINIDES Th, U, AND Pu IN COSMIC RAYS AND THEIR AGE AFTER NUCLEOSYNTHESIS

The relative abundances of the actinides permit a distinction between this model and the preceding two models. In the model of Lingenfelter et al. (1998), nucleosynthesis of the heavy nuclei (as well as C and O formed in helium burning) occurs approximately at the same time as the acceleration of cosmic rays by supernova shock waves ($\lesssim 10^7$ yr ago). In the other two models (FIP-based and grain volatility), nucleosynthesis of the heavy nuclei ($Z \geq 8$) occurs much earlier, and these nuclei (before acceleration) spend a relatively long time in flare stars or in interstellar grains.

Blake & Schramm (1974) calculated the relative abundances of the actinides as a function of time after nucleosynthesis, and Pfeiffer, Kratz, & Thielemann (1997) calculated the solar system r-process abundance. The latter

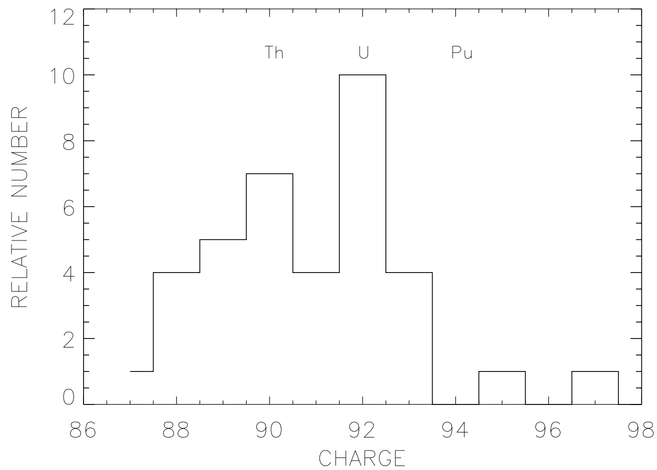

FIG. 2.—Charge distribution of actinides, based on the data of Domingo et al. (1995), Westphal et al. (1998), and Donnelly et al. (1999).

model, which uses the so-called ETFSI-*Q* mass formula, gives a ^{244}Pu/^{232}Th production ratio of 0.27. The ratios Pu/U and Pu/Th are further enhanced in 10^6 yr by the decay of ^{248}Cm into ^{244}Pu. After 10^6 yr a value of 0.4–0.5 is plausible for Pu/Th and 1 for (Pu, Cm)/Th. Donnelly et al. (1999) have measured the elemental distribution of 30 actinides, to which seven more are added from Domingo et al. (1995) and Westphal et al. (1998), shown in Figure 2. Th and U are nearly resolved, with 10% of Th and U in the unresolved region (at $Z = 91$) between $Z = 90$ and 92. These four unresolved nuclei have been assigned as follows: two to Th and two to U. Because of the spread in charge identification, the spurious charges 87–89 are added to thorium and 93 to uranium. The charge assignment is then $\approx$19 Th, $\approx$16 U, and $\approx$2 Pu or Cm, i.e., $\approx$10% transuranic nuclei.

TABLE 2

ABUNDANCE RATIOS AFTER NUCLEOSYNTHESIS (B-S) AND IN TIME INTERVALS (P-W)

Ratio	B-S[a] (4×10^7 yr)	P-W[b] (4×10^7 yr)	Measured[c]
(U, Pu, Cm)/Th	4	3	1.0 ± 0.4
(Pu, Cm)/Th	1	1	0.10 ± 0.07

[a] Blake & Schramm 1974.
[b] Pfeiffer, quoted in Westphal et al. 1999.
[c] Domingo et al. 1995; Westphal et al. 1998; Donnelly et al. 1999.

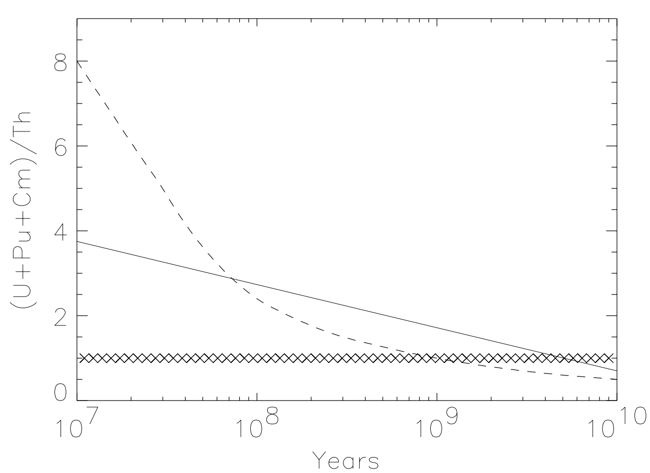

FIG. 3.—(U, Pu, Cm)/Th ratio as function of time after nucleosynthesis (*dashed line*) derived from the data of Blake & Schramm (1974). The solid line shows the nucleosynthesis time interval derived from the data of Pfeiffer in Westphal et al. (1999). The croshatched line represents the measurement of Domingo et al. (1995) and Donnelly et al. (1999) from the *LDEF* experiment and of Westphal et al. (1998).

From Blake & Schramm (1974) and from Pfeiffer, as quoted by Westphal et al. (1999), we have deduced the relative abundances of (U, Pu, Cm)/Th and (Pu, Cm)/Th (shown in Table 2) for a time of $\sim 4 \times 10^7$ yr after nucleosynthesis and for a nucleosynthesis time interval of 4×10^7 yr, respectively (cf. the model of Higdon et al. 1998). In the latter model the number of transuranics should equal the number of Th events. The calculated values for the model of Higdon et al. (1998) deviate by about 10 standard deviations for (Pu, Cm)/Th and about 5 standard deviations for (U, Pu, Cm)/Th.

Figure 3 shows the ratio (U, Pu, Cm)/Th as a function of time for 10^7–10^{10} yr after nucleosynthesis and for a nucleosynthesis time interval.The value of Donnelly et al. (1999) of the *Long Duration Exposure Facility* (*LDEF*) experiment with those of Domingo et al. (1995) and Westphal et al. (1998) is also shown (they fitted a nucleosynthesis time interval near or above 10^9 yr).

7. EFFECTS OF REACCELERATION

Galactic propagation calculations start with the cosmic-ray source composition and apply nuclear spallation cross sections, leakage path length from the Galaxy, nuclear decay probabilities, ionization losses, and solar modulation so as to relate the source composition to the measured arriving composition above the Earth's atmosphere (e.g., Letaw, Silberberg, & Tsao 1993).

Propagation calculations with reacceleration (Letaw et al. 1993) employ a single rigidity-dependent escape path length without the ad hoc discontinuity required by the standard leaky-box model. Another advantage of the reacceleration model is the smaller rigidity dependence, consistent with the high degree of cosmic-ray isotropy even at high energies. The standard leaky-box model has a strong rigidity dependence of the escape path length, i.e., a smaller escape path length at high energies. Contrary to observations, the standard model predicts a high cosmic-ray anisotropy at high energies.

The parameters (especially the leakage path length) of both the distributed reacceleration model and the standard leaky-box model have to be adjusted to fit the measured abundance distribution of elements. Table 3 compares the elemental abundances ($5 \leq Z \leq 26$) measured by Engelmann et al. (1990) at 5.6 GeV nucleon^{-1} with both propagation models. The last column gives the iterated, relative source abundance. We note that both the reacceleration and the standard models do present adequate fits to the data. The estimated abundance of Fe is 10% lower than observed. Further iterations can raise the source abundance of Fe from 176 to 194. To increase the calculated value of Fe from 102 to 113, an increase in the source value by 10% to 194 is needed.

The recently measured (e.g., Connell & Simpson 1999) electron-capture isotopes of some cosmic-ray elements can help distinguish the predictions of the distributed reacceleration model from that of the standard leaky-box model.

TABLE 3

SOME MEASURED AND CALCULATED ABUNDANCES (NORMALIZED TO OXYGEN AT 1000)

Element	Measured[a]	Calculated[b]	Calculated[c]	Source
B	252 ± 3	252	285	0
C	1049 ± 6	1051	1071	879
N	252 ± 3	252	256	65
O	1000 ± 5	1000	1000	1000
F	18 ± 1	20	22	0
Ne	154 ± 2	153	159	114
Na	30 ± 0.6	29	31	10.3
Mg	205 ± 2	198	196	203
Al	33 ± 0.7	34	34	18
Si	163 ± 2	160	157	191
P	6.2 ± 0.3	6.2	6.8	0.98
S	31 ± 0.7	30	31	24.4
Cl	5.8 ± 0.3	6.1	5.7	0.03
Ar	11 ± 0.4	11	11	3.1
K	8.4 ± 0.4	8.0	8.8	0.02
Ca	19 ± 0.6	19	20	11.8
Sc	3.4 ± 0.2	3.7	4.0	0
Ti	12 ± 0.4	12	12	0.01
V	5.6 ± 0.3	5.1	5.5	0.07
Cr	13 ± 0.5	12	13	2.76
Mn	9.3 ± 0.4	9.6	10	0.05
Fe	113 ± 1	102	100	176

[a] Engelmann et al. 1990.
[b] Letaw et al. 1993.
[c] This work.

On the one hand, these isotopic abundances decrease rapidly below ≈400 MeV nucleon^{-1} because of decay by electron capture, e.g., ^{49}V → ^{49}Ti, ^{51}Cr → ^{51}V, ^{54}Mn → ^{54}Cr, and ^{55}Fe → ^{55}Mn. On the other hand, direct production by spallation of many of these decay products (^{49}Ti, ^{51}V, ^{54}Cr, ^{55}Mn) is rather small; hence, these nuclides at low energies can be assumed to have been formed by decay with characteristic energy dependence. Reacceleration shifts the energy dependence of the isotopic abundance curves to higher energies. The preliminary measurements of Connell & Simpson (1999) appear to favor the distributed reacceleration model. However, solar modulation shifts the energy spectra to lower energies, making a clear-cut distinction all the more difficult. Direct (or inferred) isotopic abundance measurements outside the heliosphere will undoubtedly shed more light on this.

8. CONCLUSIONS, CURRENT UNCERTAINTIES, AND SUGGESTED FUTURE TESTS

1. The variation of light nuclei, Be, and thus also of Li and B, from low-metallicity to high-metallicity stars implies that the first- and/or early generation cosmic rays are relatively rich in products of nucleosynthesis that yield, on spallation, the light nuclei $3 \leq Z \leq 5$ (Lingenfelter et al. 1998).
2. From the measured abundance ratios of actinides, one can infer an age of the order of 10^9 yr for their nucleosynthesis and hence their condensation into low-mass stars (flare stars) or interstellar grains for a long period of time prior to acceleration to cosmic-ray energies.
3. Even early generation cosmic-rays can be rich in products of the He-burning products C and O. The massive, first-generation presupernova stars could shed their H and He envelopes; thereafter the presupernova wind is likely to be rich in products of helium burning. C and O are the most likely progenitors of the light elements Li, Be, and B. Models incorporating stellar evolution, mass loss, and nucleosynthesis calculations of massive first-generation stars that consist of hydrogen and helium are needed to refine the above scenarios.
4. The statistical precision desirable for estimating the abundance of Th, U, and Pu requires better charge resolution, i.e., a more precise calibration of the *LDEF* data and similar future measurements.
5. The relative abundance of Ge in cosmic rays needs further measurement. Also, the solar flare particle measurements need improved statistics. The abundance of Ge should provide a crucial test between the FIP-based and grain volatility models.

This work has been supported by NASA grant NAG 5-5165 and by NSF grant 98-10653 and NASA-JOVE grant NAG 8-1208 (A. F. B.). R. S. thanks J.-P. Meyer for valuable correspondence. The authors thank the Naval Research Laboratory for use of their computing facilities.

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